Appendix F - Estimation of Capacity

1. Introduction

For estimating the capacity of the highway and railroads we used information available at the Arizona Department of Transportation (ADOT), at the *Secretaria de Comunicaciones y Transportes* (SCT), the Federal Railroad Administration (FRA) and the US Department of Transportation (DOT). Other sources of data were the Geographic Information System (GIS) maps provided by the Environmental Systems Research Institute (ESRI) ArcInfo software, together with its companion database maps of the World (2004). The detailed procedures for each link and node in the network of highways and railroads are explained next.

2. Highway Capacity

There exist different methods for calculating the capacity of highways according to the specific characteristics (physical and flow) of the road segments. For deciding among the different methods we used the criteria provided by Highway Performance Monitoring System (HPMS 2000) presented in Figure 1.

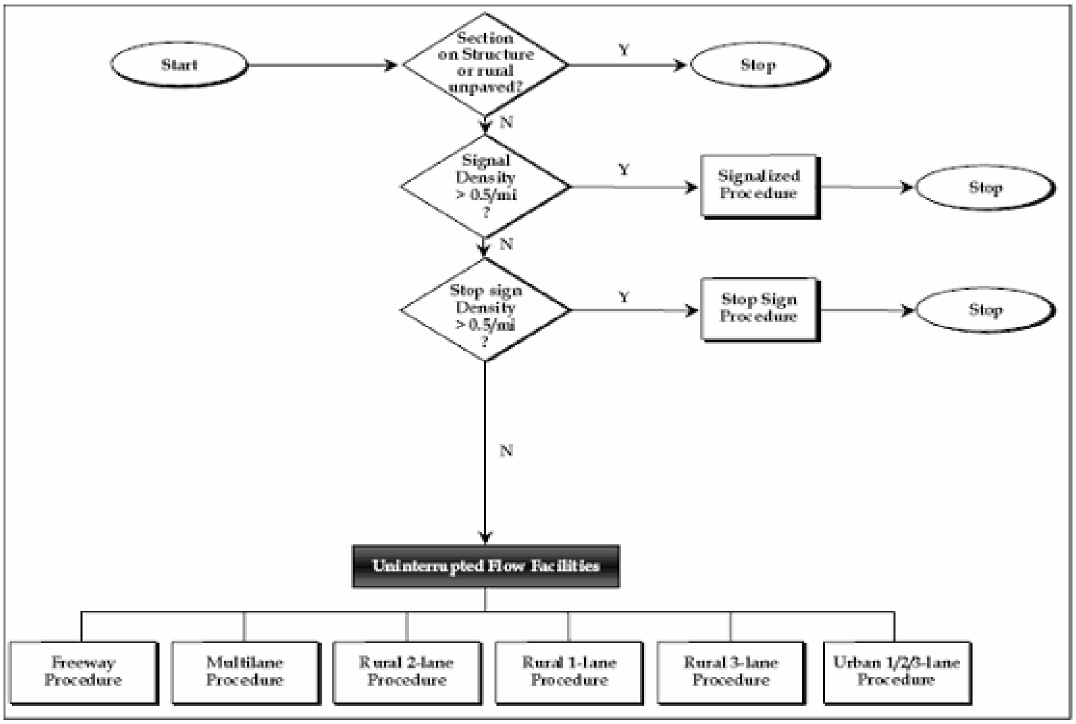

Figure 1 – Criteria for Selecting Capacity Calculation Procedures

Following the criteria from HPMS we determined the different types of roads present in the corridor (Figure 2). According to this classification we require the use of the freeway procedure for the I-19 highway and the Multi-lane highway for most of the Mexican roads, with the exception of the road between Empalme and Guaymas, which requires the two-lane procedure. Other types of roads include the urban streets in Hermosillo, Nogales, Benjamin Hill and Santa Ana.

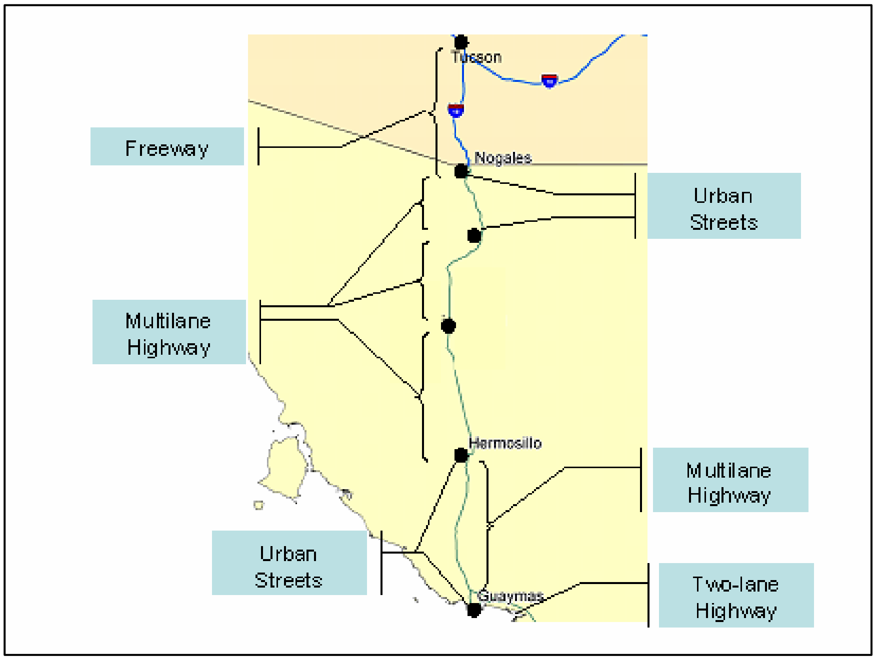

Figure 2 – Classification of the Roads in the Corridor

We also present the procedures necessary to calculate the highway capacity according to HPMS (2001) capacity calculations. This appendix shows the detailed information and calculations necessary to estimate the capacity, volume and level of service (LOS) of a given highway. The detailed procedures are presented next:

2.1. Freeway Procedure

The main difference between freeways and multilane highways is that in the case of freeways, these roads are separated from the rest of the traffic and can only be accessed by ramps. The data required for calculating the capacity of the highway according to Highway capacity manual (HCM) is the one presented in Table 1; this table also includes some default parameters that can be used when specific data is not available for the roads. However, following the recommendations from the manual we collected as much data as possible by performing physical inspections of the roads and from the data collected by ADOT and SCT.

Table 1 — Required Input Data for Freeway Segments

Required Data	Defaults
Geometric Data	
Number of lanes	--
Lane width	3.6 m
Lateral clearance	3.0 m
Interchange density	--
Specific grade and general terrain	Level
Base free-flow speed	120 km/h rural, 110 km/h urban
Demand Data	
Length of analysis period	15 min
Peak-hour factor	0.88 rural, 0.92 urban
Percentage of heavy vehicles	10% rural, 5% urban
Driver population factor	1.00

Step 1: Calculate Free Flow Speed (FSS)

The first step in the procedure is to estimate free flow speed (FFS) of the facility. HCM Equation (1) is applied directly:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID}, \tag{1}$$

where

$BFFS$ = base free flow speed

f_{LW} = adjustment factor for lane width

f_{LC} = adjustment factor for right shoulder lateral clearance

f_N = adjustment factor for number of lanes

f_{ID} = adjustment factor for interchange density

Base Free Flow Speed

BFFS is set at 70 mph for urban facilities and 75 mph for rural facilities.

Step 2: Calculate Base Capacity (*BaseCap*)

The Base Capacity (passenger cars per hour per lane; pcphpl) of a freeway facility is based on information found in HCM Exhibit 23-3. The following equations were developed based on this information:

$$\begin{aligned} &BaseCap = 1{,}700 + 10FFS;\ \text{for } FFS <= 70 \\ &BaseCap = 2{,}400;\ \text{for } FFS > 70 \end{aligned} \tag{2}$$

Step 3: Determine Peak Capacity (*PeakCap*)

The *HCM 2000* procedure does not make adjustments to the Base Capacity in order to calculate level of service and performance measures. Instead, adjustments are made to the hourly demand volume. However, for HPMS, the capacity of the segment, in terms of total vehicles per hour (vph), must be computed for a variety of analytic purposes. Therefore, the same factors used in the *HCM 2000* to adjust volume are used to adjust base capacity instead. Essentially, these adjustments convert the units from passenger cars to vehicles and lower capacity to account for the effect of heavy vehicles. The procedure is based on *HCM* Equation (2):

$$PeakCap = BaseCap * PHF * N * f_{HV} - f_P, \quad (3)$$

where

PeakCap = HPMS Peak Capacity (Data Item 95), vehicles per hour (all lanes, one direction)

PHF = Peak Hour Factor

N = Number of lanes in one direction. Number of Peak Lanes (Data Item 87)

F_{HV} = adjustment factor for heavy vehicles

f_P = adjustment factor for driver population

Following this same procedure we calculated the capacity and LOS of the I-19 highway. We then compared our results with the ones provided by ADOT, which render a difference within 3% between both capacities. We considered this difference as acceptable, given that the LOS in all the highways in the US and Mexico are not critical with the exception of the junction between the I-19 and I-10 highways. Then the results provided from our calculations are a reasonable assumption that should not overturn the results obtained.

2.2. Multilane Highway Procedure

In the case of the multilane highway, the roads have two or more lanes in each direction with a divided flow in both directions. The main difference with the freeway is that multilane highways have at grade crossings and sometimes can be accessed freely by merging traffic to the highway. The data required by multilane highways according to the HCM manual is presented by Table 2. As it was the case with the Freeway, Table 2 not only presents the information required, but some of the default parameters that should be used in the absence of specific data for the highways.

Table 2 — Default Parameters

Required Data	Defaults
Geometric Data	
Number of lanes	--
Lane width	3.6 m
Lateral clearance	1.8 m
Median (Yes/No)	--
Access-point density	Exhibit 12-4
Specific grade and general terrain	Level
Base free-flow speed	110 km/h
Demand Data	
Length of analysis period	15 min
Peak-hour factor	0.88 rural, 0.92 urban
Percentage of heavy vehicles	10% rural, 5% urban
Driver population factor	1.00

The following is the list of activities required to estimate the capacity and the LOS for every specific segment of a multilane road:

Step 1: Calculate Free Flow Speed (FFS)

The first step in the procedure is to estimate free flow speed (FSS) on the facility. HCM Equation (1) is applied directly:

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A\,, \tag{4}$$

where

$BFFS$ = base free flow speed

f_{LW} = adjustment factor for lane width

f_{LC} = adjustment factor for right shoulder lateral clearance

f_M = adjustment factor for median type

f_A = adjustment factor for access point

Step 2: Calculate Base Capacity (*BaseCap*)

The Base Capacity (passenger cars per hour per lane; pcphpl) of a multilane facility is based on the information found in HCM Exhibit 21-3. The following equations were developed based on this information:

$$\begin{aligned} &BaseCap = 1{,}000 + 20FFS;\ \text{ for } FFS <= 60 \\ &BaseCap = 2{,}200;\ \text{for } FFS > 60 \end{aligned} \tag{5}$$

Step 3: Determine Peak Capacity (*PeakCap*)

The *HCM 2000* procedure does not make adjustments to the base capacity in order to calculate level of service and performance measures. Instead, adjustments are made to the hourly demand volume. However, for HPSM, the capacity of the section, in terms of total vehicles per hour (vph), must be computed for a variety of analytic purposes. Therefore, the same factors used in the *HCM 2000* to adjust volume are used to adjust base capacity. Essentially, these adjustments convert the units from passenger cars to vehicles and lower capacity to account for the effect of heavy vehicles. The procedure is based on HCM Equation (3):

$$PeakCap = BaseCap * PHF * N * f_{HV} - f_P , \tag{6}$$

where

PeakCap = HPMS Peak Capacity (Data Item 95), vehicles per hour (all lanes, one direction)

PHF = Peak Hour Factor

N = Number of lanes in one direction. Number of Peak Lanes (Data Item 87)

F_{HV} = adjustment factor for heavy vehicles

f_P = adjustment factor for driver population. 1.0 for HPMS

2.3. Rural Two-Lane Procedure

Following the recommendations from HPMS we use the methodology that uses the average travel speed (ATS) from the HCM procedures. The data required to estimate the capacity is presented in Table 3.

Table 3 — Required Input Data: Two-Lane Highways

Required Data	Defaults
Geometric Data	
Highway class	Exhibit 12-10
Lane width	3.6 m
Shoulder width	1.8 m
Access-point density	Exhibit 12-4
Specific grade and general terrain	Level
Percent no-passing	Exhibit 12-11
Base free-flow speed	--
Length of passing lane	Exhibit 12-12
Demand Data	
Length of analysis period	15 min
Peak-hour factor	0.88 rural, 0.92 urban
Percentage of heavy vehicles	Exhibit 12-13
Driver population factor	Exhibit 12-14

$$ATS = FFS \;\; 0.00776 * V_p \; - f_{np} \tag{7}$$

where:

ATS = Average travel speed

V_P = passenger car equivalent flow rate for peak 15 minutes

f_{np} = no passing zone adjustment factor from Table 4.

Table 4 - Adjustment (fnp) for Effect of No-Passing Zones on Average Travel Speed

Two-Way Demand Flow Rate, Vp (pc/h)	Reduction in Average Travel Speed (km/h) No-Passing Zones (%)					
	0	20	40	60	80	100
0	0.0	0.0	0.0	0.0	0.0	0.0
200	0.0	1.0	2.3	3.8	4.2	5.6
400	0.0	2.7	4.3	5.6	6.3	7.3
600	0.0	2.5	3.8	4.9	5.5	6.2
800	0.0	2.2	3.1	3.9	4.3	4.9
1000	0.0	1.8	2.5	3.2	3.6	4.2
1200	0.0	1.3	2.0	2.6	3.0	3.4
1400	0.0	0.9	1.4	1.9	2.3	2.7
1600	0.0	0.9	1.3	1.7	2.1	2.4
1800	0.0	0.8	1.1	1.6	1.8	2.1
2000	0.0	0.8	1.0	1.4	1.6	1.8
2200	0.0	0.8	1.0	1.4	1.5	1.7
2400	0.0	0.8	1.0	1.3	1.5	1.7
2600	0.0	0.8	1.0	1.3	1.4	1.6
2800	0.0	0.8	1.0	1.2	1.3	1.4
3000	0.0	0.8	0.9	1.1	1.1	1.3
3200	0.0	0.8	0.9	1.0	1.0	1.1

For HPMS purposes estimates of capacity are still needed. Therefore, instead of adjusting flow rates, (volumes) capacity will be adjusted by most of the same factors:

$$Two-Way\ Capacity = (3{,}200\,pch * PHF * f_G * f_{HV}) - V_{NP} \tag{8}$$

where:

PHF = Peak Hour Factor = 0.88

f_G = Adjustment factor for heavy vehicles

f_{HV} = Adjustment factor for heavy vehicles

V_{NP} = Volumen adjustment for no passing zones

2.4. Urban Streets: Signalized Procedure

Although some states do code these items for rural sections, a provision must be made to handle cases where the data are not present; this could also be true for some urban sections. In the cases where rural signalized sections have nonzero values coded for these data items, the signalized intersection capacity is used. When these data are coded as zero, the following procedure is used:

$$CA = 1{,}900 * N * f_w * f_{HV} * PHF * g / C\,, \tag{9}$$

where:

CA = intersection approach capacity

N = number of lanes on the segment (one direction)

fw = adjustment factor for lane width (use Equation 10)

f_{HV} = adjustment factor for heavy vehicles (use Equation 11)

P_{HF} = Peak Hour Factor (0.88 for rural, 0.92 for urban condition)

g/C = effective green time-to-cycle length ratio. (0.55 for principal arterials, 0.45 for minor arterials, 0.40 for collectors)

$$f_w = 1 + \frac{(W-12)}{30} \tag{10}$$

$$f_{HV} = \frac{(100)}{100 + HV(E_T - 1)} \tag{11}$$

The g/C ratio default values given above attempt to account for, in a general way, the presence of exclusive turn lanes and phases.

2.5. Capacity of Other Facilities

For estimating the different facilities in the roads, we not only restricted ourselves to estimating the capacity of the road segments, such as the ones mentioned in Figure 1, but also to other facilities that are relevant for estimating the capacity of the corridor. These include toll roads and other type of road blocks that are not considered in the methodology for HPMS, but that are present in Mexican roads. To calculate the capacity of the toll booths in the corridor we used the information provided by the *Instituto Mexicano del Transporte* (2000), presented in Table 5. We also used the information from the Multimodal Corridor and Capacity Analysis Manual (1998) to determine the capacity of speed bumps and other particular situations along the corridor, particularly in the case of populated places, which presents on Table 6, a list of the most common facilities in any highway corridor, with its capacity estimation.

Table 5 - Capacity of Different Toll Systems

Cuadro 4.1
Comparación de Casetas y Capacidades

Clase de caseta	Capacidad en veh/hr
Atendida (Con operaciones de cambio, emisión de recibos, etc.)	350
Atendida (Sólo con distribución de boletos)	500
Automática (Sólo monedas – no fichas)	500
Automática (Básicamente fichas – pocas monedas)	650
Modo Mixto (Cualquiera de las clases anteriores y cobro electrónico)	700
Dedicada al Cobro Electrónico de Cuotas (dentro de una plaza de cobro convencional)	1,200
Cobro Electrónico Express	1,800

Fuente: Humphrey et al, 1992.

Table 6 - Highway Capacity by Facility

FACILITY	UNITS	TIME PERIOD[a]	AREA	UNITS OF FLOW	CAPACITY (IDEAL CONDITIONS)
UNINTERRUPTED FLOW FACILITIES					
Freeway					
Basic section, four lanes	Passenger cars	Hour	Lane	pcphpl[b]	2,200
Basic section, six or more lanes	Passenger cars	Hour	Lane	pcphpl	2,300
Weaving area	Passenger cars	Hour	Lane	pcphpl	1,900
Ramp junction	Passenger cars	Hour	Merge or diverge area	pcph	2,000
One-lane ramp	Passenger cars	Hour	Ramp Roadway	pcph	1,700
Multilane highway	Passenger cars	Hour	Lane	pcphpl	2,200
Two-Lane highway	Passenger cars	Hour	Both Lanes	pcph	2,800[c]
INTERRUPTED FLOW FACILITIES					
Signalized intersection	Passenger cars	Hour of Green	Lane	pcphgpl	1,900[d]
Unsignalized intersection					
Two-way stop controlled	Passenger cars	Hour	Lane or movement	pcph	1,060[e]
All-way stop controlled	Vehicles	Hour	Entering Lane	vph	500-1,100[f]
Urban arterials[g]					
Exclusive transit bus lane on urban arterial with stops	Buses	Hour	Lane	bphpl	90-120
Pedestrian Walkway	Pedestrians	Minute	Ft. of effective width	p/min/ft	25
Bikeway	Bicycles	Hour	Lane	bike/hr	2,150[h]

[a] Time periods of 1 hr. are usually based on a peak 15-min volume expanded to an "hourly rate of flow"
[b] Passenger cars per hour per lane.
[c] For 50-50 volume, split by direction.
[d] Saturation flow rate, in passenger cars per hour of green time per lane.
[e] Potential capacity with no conflicting volume.
[f] Depending on volume distribution from conflicting approaches.
[g] Capacity usually measured and controlled by most restrictive signalized intersection.
[h] Middle of reported range.

2.6. Results

Using the alternative methodology just mentioned, we developed a summary of the estimated capacity for a selected sample of segments on the road; these results are displayed on Table 7. The first segment is crossing the city of Guaymas, with its estimated flow of vehicles and the estimated capacity in vehicles per hour (not trucks), with a LOS of 0.23 or a 23% utilization of the road.

Table 7 - Capacity and Performance of the Nodes Sampled

Node	Lanes	Volume/Hr	Capacity	LOS
Guaymas	2	268.15	1180.33	0.23
Toll 1	3	140.00	1050.00	0.13
Hermosillo3	2	556.05	1142.86	0.49
Toll 2	3	216.00	1050.00	0.21
Benjamin Hill	2	226.17	702.00	0.32
Santa Ana	2	173.71	1152.00	0.15
Toll 3	3	224.00	1050.00	0.21
Imuris	2	224.16	1152.00	0.19
Toll 4	3	294.00	1050.00	0.28
Nogales, AZ	3	872.00	1672.00	0.52
Tucson	2	4314.00	4271.00	1.01

3. Railroad Capacity

3.1. Single Track Rail Freight Capacity

The characteristics of the railway in the Corridor are consistent at both sides of the border from the Port of Guaymas to the City of Tucson. The railway has a single line without block signals. The regular size of the trains in this corridor is around 105 cars that can have an approximate length of 6,500 feet. The size of the trains limits the use of the sidings available, so the sidings used in the corridor are in Table 8.

Table 8 –Corridor Sidings

	Length (meters)	Km.
Sidings between Tucson-Nogales:		
Sahuarita	2,440	-76
Rio Rico	1,830	-14
Sidings between Nogales-Hermosillo:		
Agua Sarca (Medium)	1,851	18
Imuris	2,704	64
Benjamin Hill	2,831	150
Carbo	3,207	208
There are 3 additional sidings in the Hermosillo-Emplame line:		
Torres	1935	318
Moreno	2138	349
Santa Rosa	1903	389
The main stations in the rail line are:		
Tucson		-105
Nogales		0
Hermosillo		269
Emplame		413

3.2. Methodology

The methodology we used to calculate the capacity of the railway was developed by PMM & CO. (Peat, Marwick and Mitchell, 1975). Their method was specifically developed for the Federal Rail Road Administration (FRA). The procedure is based on the parametric analysis of a series of rail line cases simulated by a computer train dispatching model. The main contribution of this method is the use of regression techniques to the analysis of different types of trains and the application of these formulas without having to develop simulation models for different characteristics of the trains.

The main factors considered in the analysis are the average speed of the trains, the average spacing between the sidings on the line and the use of block signals and the space between them.

These different parameters generate delays for the trains that are dispatched on the railroad on a given day. For example the use of sidings spaced at around 21.8 miles (Figure 3) generates delays of around an hour per train when approximately 10 trains use a segment of 100 miles on a given day. That indicates that the total running time of the train has been reduced, reducing at the same time the capacity of the railway. The same criterion is used for the rest of the factors we use for the analysis of the railroads: Train speed (Figure 4) and block signal spacing (Figure 5). These 3 factors have the highest contribution to the capacity of the railway, so we only focus on these 3 for the purpose of our rough capacity estimate.

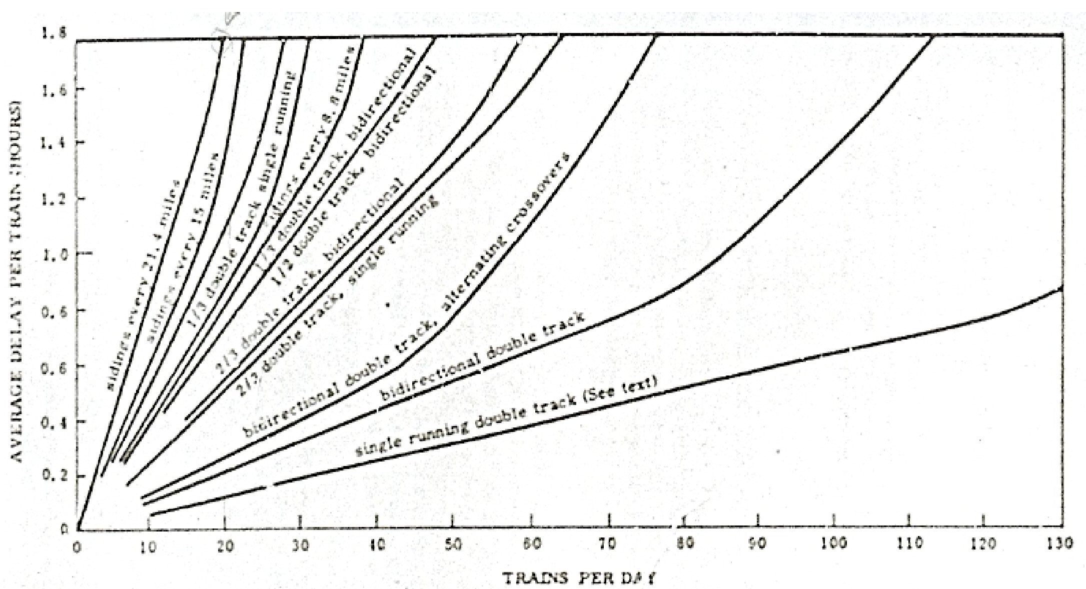

Figure 3 – Train Volume-Average Delay Relationship for Configurations of 100 Mile Rail Line

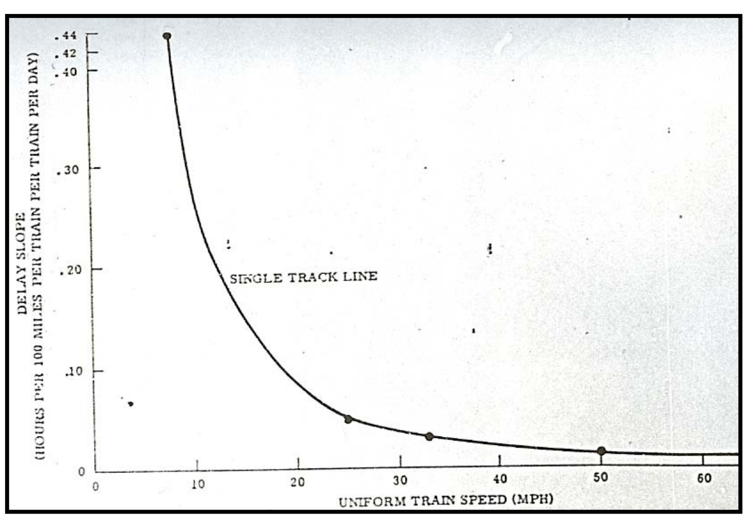

Figure 4 – Delay Slope vs. Uniform Speed

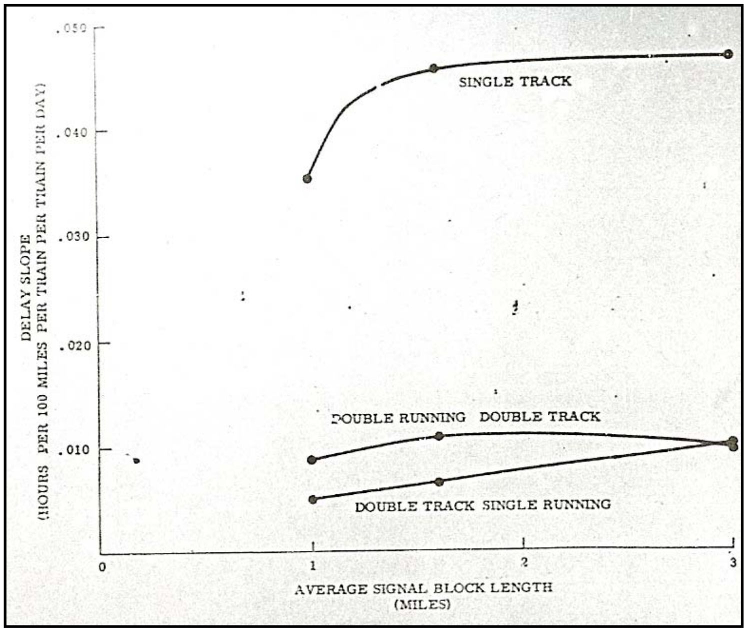

Figure 5 – Delay Slope vs. Block Length

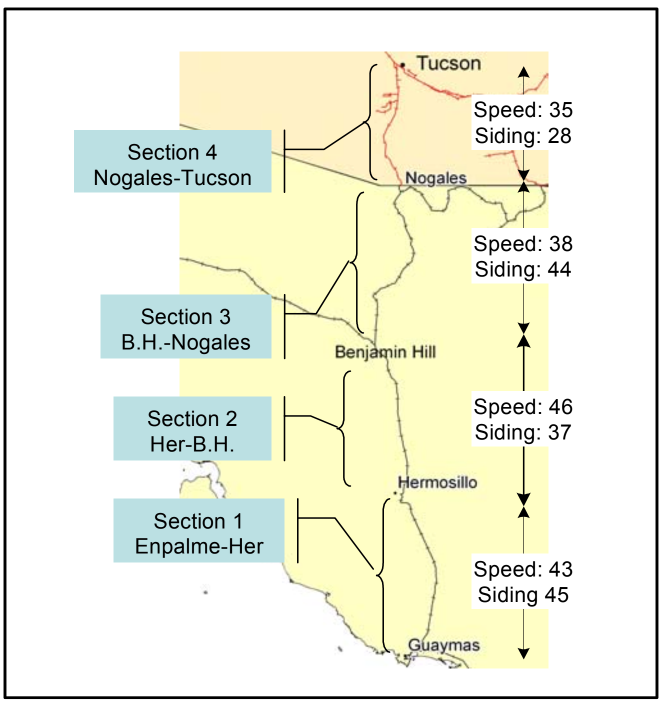

Figure 6 — Characteristics of the Railroad Sections

Following this methodology in Figure 6 we present the main railroad sections of the corridor together with the information of the main factors required for the calculating its capacity. As we can see the Mexican side has been partitioned in 3 segments, from Emplame-Hermosillo, Hermosillo-Benjamin Hill and Benjamin-Hill-Nogales. The American side from Nogales to Tucson is considered as a single segment. In the following sections we describe in detail the estimation of the capacity following PMM's methodology.

The capacity of the railway is calculated based on the delay that the trains are forced to endure and the effects of that delay in the capacity of the rail line. The Modal capacity of a railway with a single line, line in terms of maximum permissible delay, expressed in trains per day is the following:

$$C = \frac{A_c}{K}\left(\frac{100}{L}\right). \tag{9}$$

where,

- C: Measure of modal capacity in trains per day,
- Ac: Average delay per train at capacity (in hours, exclusive of scheduled delays),
- K: Delay slope (for a 100 mile line),
- L: Length of line (in miles),

$$A_c = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \text{, is the average delay per train, in hours.} \tag{10}$$

$$a = 973.125 * \frac{S}{L^2},$$

$$b = \frac{67.2765 * P + 151.7085 * D}{L},$$

$$c = 1.41432 - M\left(\frac{150}{L}\right) + \frac{150}{S} + I,$$

where,

M = Maximum allowable total running time (12 hours less allowance for terminal time).
S = The speed of the slowest class of through trains
P = Dispatching peak factor = (trains per peak hour during peak/ trains peak hour off peak)-1
D = Directional factor = (trains in dominant direction/trains in opposite direction)-1
I = Amount of imposed delays on regular freight trains (such as required stops including the start and stop time)

3.3. Calculating the Delay Slope (*K*)

The parameters of each one of the factors (speed, sidings and block signals) are compared against the base model (Table 9). The difference between them has to be considered and its effect should modify the results obtained. The way to include the effects of these factors for our particular system is by calculating the difference with the base model:

$$K = f_m K_o \text{ (Delay slope, expressed in hours per 100 miles)} \tag{11}$$

where,

K_o = Delay slope for the base case

f_m = Compounded effects of the different factors compared to the base case.

K_o = 0.04538 (Base case scenario)

$$f_m = C_i / C_d \tag{12}$$

where,

C_i = Component of factors which increase the slope

C_d = Component of factors which decrease the slope

$$C_i = \left[\left(\sum f_{oi}{}^{Pi}\right) - (N_I - 1)\right]$$
$$C_d = \left[\left(\sum f_{oi}{}^{-Pi}\right) - \left(N_D - 1\right)\right] \tag{13}$$

where,

N_I = Number of slope increasing modifications

N_D = Number of slope decreasing modifications

f_{oi} = The delay adjustment factor

P_i = The percent change in parameter i

$$P_i = \frac{(V_i - V_o)}{1/2(V_i + V_o)}, \tag{14}$$

where V_i is the data we obtained from the system and V_o is the parameter from the base model. The data for the base model can be consulted on Table 9 which represents the default data for the base model. Consulting Table 9 we can find the values for V_o and V_i for the most important policy variables. As mentioned before we concentrated for the purpose of the current system in only 3 changes to the base model: speed, average space between sidings and block signals. The other parameters are assumed the same as the ones for the base case with a single rail line shown in Table 9.

The Assumptions We Used for All the Segments are the Following:

M = 10 hours

P = 0 (No peaking)

D = 0 (No imbalance)

I = 1.233

Table 9 - Policy Variables and Parameters for Modifying the Base Case

Type	Modification	Policy Variable	Unit (V_1)	Base Value (V_o)
A	Change block size	Average block size	Miles	1.8 mi
B	Change train priority	Train priority	No Priority: 3/2 Base Priorities: 1/2	1/2
C	Change station spacing	Average segment size	Miles	8.82 mi
D	Select uniform or non-uniform speed	Train speed uniformity	Base Speeds by Class: 1/2 Uniform Speeds: 3/2	1/2
E	Change uniform speed	Uniform Train Speed	mph	32.8 mph
F	Change proportional speed	Average Train Speed	mph	32.8 mph
G	Change siding capacity	Siding Capacity	Base Capacity: 1/2 Double Capacity: 3/2	1/2
H	Select uniform or non-uniform segments	Segment uniformity	Non-Uniform: 1/2 Uniform: 3/2	1/2
I	Select dispatch peaking or non-peaking	Fraction daily volume in peak/ Fraction of day in peak	Peaking Fraction	1
J	Select rare events or non-rare events	Presence of rare events	Rare events: 1/2 Non-rare events: 3/2	1/2
K	Change train length	Train length as fraction of base length	Train length as fraction of base length	1
L	Change directional imbalance	No. of trains in heavy direction/ No. of trains in light direction	Directional Imbalance Fraction	1
M	Select base blocks or 1 block between stations	Same as modification	Base block configuration: 1/2 1 Block between stations: 3/2	1/2
N	Select full cross-over or alternate directional cross-overs	General double-track crossover flexibility	Full: 1/2 Alternate: 3/2	1/2
P	Change fraction double track	Fraction of line mileage with double track	Double: 1 1-in-3 Single: 0.7 1-in-2 Single: 0.533 2-in-3 Single: 0.3467 Single: 0	0 or 1

Detailed Information for Each One of the Segments:

Empalme – Hermosillo

L = 140.6 Km = 87.36479 mi
Average speed = 43 mi/hr
Average distance between sidings: 45 miles
S= 43 miles (Speed of slowest train)

Hermosillo – Benjamin Hill

L = 126.1 Km = 78.35491 mi
Average speed = 46 mi/hr
Average distance between sidings: 37 miles
S= 43 miles (Speed of slowest train)

Benjamin Hill – Nogales:

L = 144.9 Km = 90.03669 mi
Average speed = 38 mi/hr
Average distance between sidings: 44 miles
S= 43 miles (Speed of slowest train)

Nogales-Tucson:

L = 65 miles
Average speed = 35 mi/hr
Average distance between sidings: 28.4 miles
S= 35 miles (Speed of slowest train)

Following this methodology, we demonstrate the calculations performed to get the capacity of the first segment (Empalme-Hermosillo). Using the information provided we made 4 modifications to the base case scenario. The first change involved the average speed of the train over the segment from 32.8 to 43 miles per hour. The second change was a modification to the speeds of trains, since the base case assumes that some classes of trains have different speeds, but in our case all the trains run at the same speed. The third modification consisted in the use of block assignments, between the sidings, since blocks are segments of the railroad assigned to a single train through the control of a central dispatcher, and they assign according to the sidings available. Finally the average space between sidings was changed from the base case of 8.82 to 45 miles on average.

For each of these changes we required the delay adjustment factor (f_{oi}) for each of the cases, obtained from Table 10. One example is the use of the f_{oi} for siding average spacing, since in our case the number is 43 miles, then we look in Table 10 for the closest case for siding separation, which is 21.4 miles, so we use the adjustment factor 2.8556 from that table.

Table 10 - Delay Adjustment Factors for Different Changes to the Base Case

Case No.	Modifications From Primary Base	No. of Tracks D: Double Runs S: Single Runs	Base Case No.	K	K_1	P_i	f_{oi}
1	Single Track Base Case	1	--	0.04538	0.001867	-1	0.9450
2	5-mile Segments	1	1	0.03108	0.001324	-0.561	1.7752
3	15-mile Segments	1	1	0.06026	0.003825	+0.510	1.9486
4	21.4-mile Segments	1	3	0.08728	0.004935	+0.353	2.8558
5	Uniform Segments	1	1	0.03387	0.001360	+1	0.7897
6	33% Decrease in Speeds	1	1	0.06421	0.004277	-0.395	0.4154
7	40% Increase in Speeds	1	1	0.02226	0.000713	+0.333	0.1395
8	8 mph Uniform Speed	1	9	0.43867	*	-1.030	0.1124
9	25 mph Uniform Speed	1	10	0.04592	0.002781	-0.270	0.2140
10	32.8 mph Uniform Speed	1	1	0.03029	0.001119	+1	0.7062
11	50 mph Uniform Speed	1	10	0.01286	0.000435	+0.415	0.1221
12	70 mph Uniform Speed	1	11	0.00991	0.000281	+0.333	0.4799
13	1-mile Blocks, 4 Aspects	1	1	0.03515	0.001423	-0.462	1.5378
14	3-mile Blocks	1	1	0.04663	0.001919	+0.609	1.1475
15	1 Block Between Stations	1	1	0.12203	0.006365	+1	2.6890
16	Double Siding Lengths	1	1	0.03932	0.001317	+1	0.9170
17	1.5 Length Trains	1	1	0.04681	0.002020	+0.400	1.0806
18	Double Train Lengths	1	17	0.05609	0.004409	+0.286	1.8823
19	Double Length, One Way	1	1	0.05694	0.003516	+0.667	1.4053
20	Coincident Peaks	1	1	0.04179	0.002345	+0.824	0.9049
21	Separate Peaks	1	1	0.03329	0.002077	+0.824	0.6866
22	1:2 Directional Imbalance, No Rare Events	1	25	0.03169	0.001038	+0.667	0.7834
23	1:4 Directional Imbalance, No Rare Events	1	22	0.02563	0.000870	+0.667	0.7273
24	No Priorities	1	1	0.02981	0.001183	+1	0.6569
25	No Rare Events	1	1	0.03730	0.001540	+1	0.8219
26	Double Track, Double Run Base	2 D	43	0.01067	0.000137	-1	0.8029
27	2 in 3 Segments Single	2 D	28	0.04179	0.001235	-0.424	0.7436
28	1 in 2 Segments Single	2 D	29	0.03685	*	-0.271	0.3438
29	1 in 3 Segments Single	2 D	26	0.02759	*	-0.353	0.0677
30	5-mile Segments	2 D	26	0.00856	*	-0.561	1.4819
31	15-mile Segments	2 D	26	0.00840	0.000162	+0.510	0.6280
32	Uniform Station Spacing	2 D	26	0.00913	0.000164	+1	0.8563
33	33% Decrease in Speed & Uniformity	2 D	26	0.01645	*	-0.395	0.3343
34	40% Increase in Speeds & Uniformity	2 D	26	0.00547	0.000100	+0.333	0.1349
35	1-mile Blocks, 4 Aspects	2 D	26	0.00856	*	-0.462	1.6122
36	3-mile Blocks	2 D	26	0.00956	*	+0.609	0.8346
37	Coincident Peaks	2 D	26	0.01022	*	+0.824	0.9498
38	Separate Peaks	2 D	26	0.00767	*	+0.824	0.6698
39	1:4 Directional Imbalance, No Rare Events	2 D	41	0.00752	0.000092	+0.667	0.9716
40	No Priorities	2 D	26	0.00767	*	+1	0.7188
41	No Rare Events	2 D	26	0.00767	*	+1	0.7187
42	Alternate Direction Crossovers	2 D	26	0.01336	0.000308	+1	1.2520
43	Double Track, Single Run Base	2 S	26	0.00643	0.000052	+1	0.6029
44	2 in 3 Segments Single	2 S	45	0.05574	*	-0.675	0.3286
45	1 in 3 Segments Single	2 S	43	0.02630	*	-0.353	0.0185
46	40% Increase in Speeds and Uniformity	2 S	43	0.00278	*	+0.333	0.0804
47	1-mile Blocks, 4 Aspects	2 S	43	0.00522	*	-0.462	1.5695
48	3-mile Blocks	2 S	43	0.01011	*	+0.609	2.1023
49	Coincident Peaks	2 S	43	0.00856	*	+0.824	1.4139
50	No Rare Events	2 S	43	0.00487	*	+1	0.7257

The results of these changes are presented in Table 11, where we show the use of the formulas (14), (13), (12) and (11) to calculate the delay slope (K), which is 2.5079*.04538= 0.1138 according to Formula (11).

Table 11 - Calculation of the Compounded Effect of the Different Factors

	V_o	V_i	P_i	f_{oi}	C_i	C_d	f_m	K
Speed	32.8	43.0	0.2691	0.7062		1.0981		
Uniform	0.5	1.5	1.0000	0.7062		1.4160		
Block	0.5	1.5	1.0000	2.6890	2.6890			
Siding	21.4	45.0	0.7108	2.8558	2.1084			
				Σ	3.7974	1.5142	2.5079	0.1138

The second result we need is the average delay per train at capacity (A_c) from Formula (10) obtained in the following calculation:

$$A_c = \frac{\sqrt{-4(5.3548)(-10.951)}}{2(5.3548)} = 1.43$$

Finally we use the results from the delay slope Formula (9), and the average delay per train at capacity (Ac) from Formula (10):

$$C = \frac{1.43}{.1138}\left(\frac{100}{87.4}\right) = 14.38$$

We follow this same methodology for all the remaining segments of the railroad, and we present a summary of these results in Table 12.

Table 12 - Results of Capacity and Utilization for the Different Line Segments

Segment	Speed	Block	Sidings	Length	Capacity	Volume	Utilization
Emplame-Hermosillo	43	1	45	87	14	6	42%
Hermosillo-B.H.	46	1	37	78	18	6	34%
B.H.-Nogales	38	1	44	90	14	6	44%
Nogales-Tucson	35	1	29	65	19	6	31%

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